Finite element analysis on the effect of the incorporation of miniscrews in palatal expanders

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Finite element analysis on the effect of the incorporation of miniscrews in palatal expanders

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2012 년 7 월

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Abstract

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In adults, because of increased resistance from bony palate and zygomatic buttress many clinicians have adjudged surgically assisted RPE(SARPE) is a treatment choice. Because of several limitations of SARPE such as economic problem, surgical morbidity, needs of two stage surgery and complexity of treatment process, there have been several efforts to reduce surgical risks for young adults who have transverse deficiency. However, the effect and stress distribution of various devices, conventional RPE, bone-borne RPE and MARPE in young adults is not yet clearly understood. Therefore, the purpose of this study was to evaluate the stress distribution and displacement of various craniofacial structures after nonsurgical RPE in young adults according to the appliance design, the position and the number of miniscrews, using 3-dimensional finite element study.

1. Conventional RPE induced the highest stress, although the maximum stress was on the frontal process of the maxilla and around the anchor teeth and not on the suture area. As the combination type of bone- and tooth-borne RPE, MARPE showed a relatively even stress distribution and reduced stress on the buccal plate of the anchor teeth. Bone-borne RPE was expected to be the most effective as an alternative of SARPE. However, the stress was highly concentrated around the miniscrews, rather than being transferred to the basal bone and the whole midpalatal suture.

2. Even when 2 or 4 miniscrews were added to the bone-bone RPE, the stress remained extremely concentrated around the miniscrews, and the expansion force was not transferred to the basal bone under any condition.

3. With both the bone-borne RPE and MARPE with 4 miniscrews, the stress was more evenly distributed and the maximum stress value was decreased when the miniscrews were located on the lateral palatal slope compared to when they were located in the midpalatal area.

Key words: Finite element analysis, FEM, Miniscrew, RPE, stress distribution, Bone and tooth borne RPE

Finite element analysis on the effect of the incorporation of miniscrews in palatal expanders

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(Directed by prof. Kee-Joon Lee)

I. Introduction

Rapid palatal expansion (RPE) has been used as an effective treatment modality in growing patients since its first introduction by Angell[1] in 1860. Because of the increased resistance from the bony palate and zygomatic buttress,[2,3] surgically assisted RPE (SARPE) is often used in adults. However, SARPE is associated with several limitations, including high cost, surgical morbidity, a 2-stage surgery, and a complex treatment process. Therefore, efforts have been made to reduce the surgical risks for young adults who have a transverse deficiency.

Midpalatal suture morphological development can be divided into 3 stages[4]. The suture begins as a short, broad, Y-shaped structure, which becomes more sinuous in the second stage and undergoes heavy interdigitation in the third stage. Although once thought to be obliterated during the juvenile period, histological studies[5,6] have shown that the midpalatal suture rarely shows a marked degree of closure before the third decade of life. Moreover, a radiologically invisible suture does not indicate histological fusion or closure. Consequently, nonsurgical RPE may be a feasible treatment protocol in young adults with a patent suture[7].

Nonsurgical RPE can produce unwanted effects when used in skeletally mature patients, such as lateral tipping of the posterior teeth, buccal root resorption, fenestration of the buccal cortex, and inability of expansion. Excessive stress can be concentrated on the maxillary buccal cortex because of the increased rigidity of the maxillary articulations with the face. To be successful, orthodontic expansion in adults should employ a higher level of force[8] and relatively slower expansion rate than that used in younger persons[9]. Increasing the rigidity of the expander and the connecting wire reduces the moment induced by the offset from the dentomaxillary center of resistance[10].

Nonsurgical RPE can be achieved through conventional, bone-borne, and combination-type RPEs. Bone-anchored devices have been shown to result in successful RPE in adults[11,12]. Although an additional surgical procedure was conducted, the authors suggested that use of miniscrew in the palatal area would be helpful. In addition to several reports[7,13] of successful nonsurgical expansion in young adults by conventional RPE, Lee[14] introduced a miniscrew-assisted RPE (MARPE) as a combination-type RPE for the delivery of an expansion force directly to the basal bone. When used in a young adult patient, MARPE achieved adequate nonsurgical expansion of the maxillary buccal segments.

To visualize and quantify the initial displacement and stress distribution of an orthodontic force, finite element analysis (FEA) produces a three-dimensional (3D) computational model to analyze the stress and strain distributions and the value of the moment[15-17]. The FEA parameters can be altered to simulate various conditions. Although FEA studies have provided detailed knowledge regarding the RPE technique in growing patients[18-21], the effects and stress distribution of various devices, including conventional RPE, bone-borne RPE, and MARPE, in young adults are not yet clearly understood.

In the present study, 3D FEA was utilized to analyze the stress distribution and displacement of various craniofacial structures after nonsurgical RPE in young adults, according to the appliance design and the position and number of miniscrews.

II. Materials and methods

1. Construction of finite element model

1) Construction of skull model

Computed tomography (CT) was performed on the dry human skull of a 20-year-old male. The skull, excluding the mandible, was inspected for gross defects and discontinuities in the craniofacial anatomy. Sequential CT images were taken at 2-mm intervals in the axial direction, parallel to the Frankfort plane. Images were reconstructed layer by layer to obtain the 3D FE model. Given the complexity of the bone structures and their interactions with the surrounding structures via sutures, the simplifications introduced by Tanne et al.[22,23] were applied to the model. Based on the studies of Knaup[24] and Wehrbein[6] for the assessment of cranial sutures, the suture thickness was uniformly set to 0.2 mm (Fig. 1).

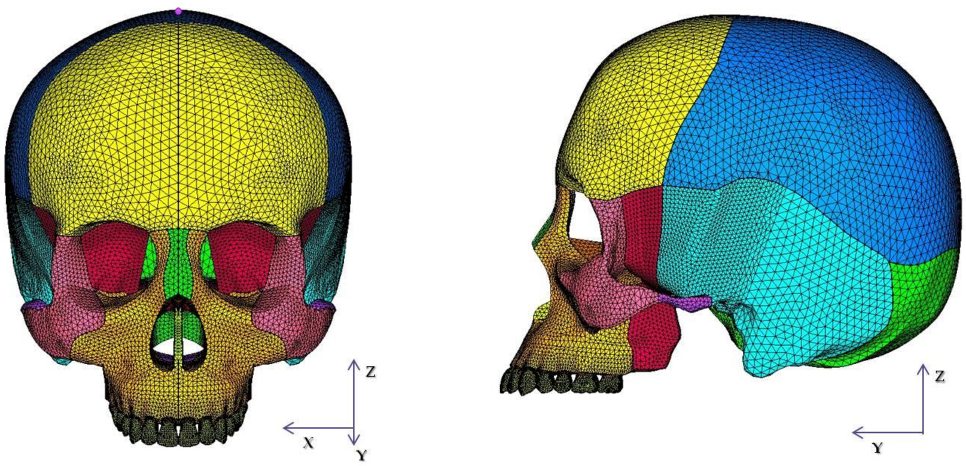


Figure 1. The 3D finite element model used in this study

2) Teeth, periodontal ligament, and alveolar bone

The Nissin dental model (Nissin Dental Products, Kyoto, Japan) from a sample survey of adults with normal occlusion was scanned in 3D and constructed. The dental arch was arranged in broad arch form from Ormco (CA, USA), and the inclination and angulation of each tooth were set by Andrews prescription[25]. The periodontal ligament thickness was uniformly set to 0.25 mm, in accordance with Coolidge[26] and Kronfeld[27]. Under the assumption that the alveolar bone was in the normal condition, it was built up at 1 mm away from and along the curvature of the CEJ.

3) Mechanical properties

Because this study was designed to investigate the initial reaction to an orthopedic expansion force, the teeth, alveolar bone, periodontal ligament, suture, and supporting wire were assumed to be homogeneous, isotropic, and linearly elastic. The mechanical properties of the components of the model were obtained from experimental data in previous studies[17,21,28,29] (Table 1).

Table 1. Material properties

	Young's modulus (g/mm^2)	**Poisson's ratio**
Cancellous bone	2.0E+05	0.30
Compact bone	2.0E+06	0.30
Suture	5.0E+03	0.30
Periodontal ligament	5.0E+03	0.49
Teeth	2.0E+06	0.30
Stainless steel	2.0E+07	0.30

2. Appliance design and experimental conditions

Figures 2–4 show schema for the appliance design and experimental conditions.

1) Effect of tooth- or bone- borne appliances.

Conditions 1–3 were designed to examine the effects of tooth- or bone-borne appliances with a miniscrew length of 7 mm.

Condition 1 utilized a tooth-borne RPE (conventional RPE). A conventional hyrax expander was designed, which incorporated the first premolars and first molars.

***Condition* 2** utilized a bone-borne RPE (expander + 4 miniscrews). Four rigid connectors of stainless steel wire (0.8 mm diameter) were soldered on the base of a hyrax screw body to orthodontic miniscrews (2.0 mm diameter, 7 mm length). Two anterior miniscrews were positioned on the rugae region between the central and lateral incisor roots. Two posterior miniscrews were placed on the parasagittal area.

Condition 3 utilized a MARPE (combination type, tooth-borne RPE + 4 miniscrews). The expander had connectors to both the teeth and the miniscrews. The position of the miniscrews was the same as in condition 2.

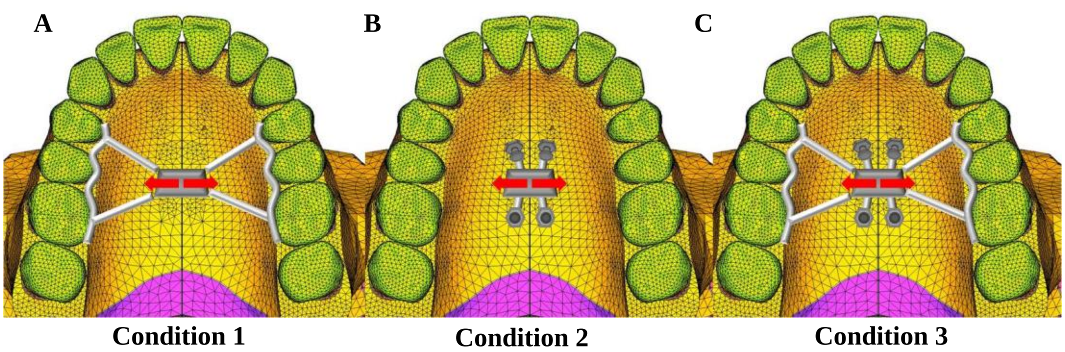
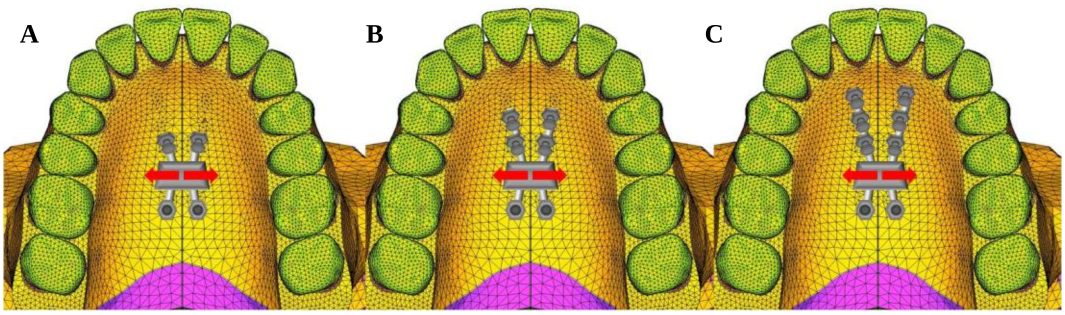


Figure 2. Appliance design and experimental conditions 1, 2, and 3. A, Tooth-borne RPE; B, bone-borne RPE; C, MARPE

2) Effect of the number of miniscrews

Conditions 2, ***4***, and ***5*** were designed to examine the effect of using 4, 6, and 8 miniscrews, respectively, in the midpalatal area.

Posterior miniscrews were positioned on the parasagittal area within 3 mm of the midpalatal suture. Anterior miniscrews were positioned between the central and lateral incisors, with 5 mm interval from the palatal expander and perpendicular to the palatal bone surface.



Condition 2 **Condition 4** **Condition 5**

Figure 3. Appliance design and experimental conditions 2, 4, and 5. A, Bone-borne RPE with 4 miniscrews; B, bone-borne RPE with 6 miniscrews; C, bone-borne RPE with 8 miniscrews.

3) Effect of the position of miniscrews

Conditions 6 and ***7*** utilized a bone-borne RPE and a MARPE, respectively, with 4 miniscrews on the lateral palatal slope area. Lateral miniscrews were positioned on the lateral palatal slope between the premolars and molars at less than 7mm from the CEJ

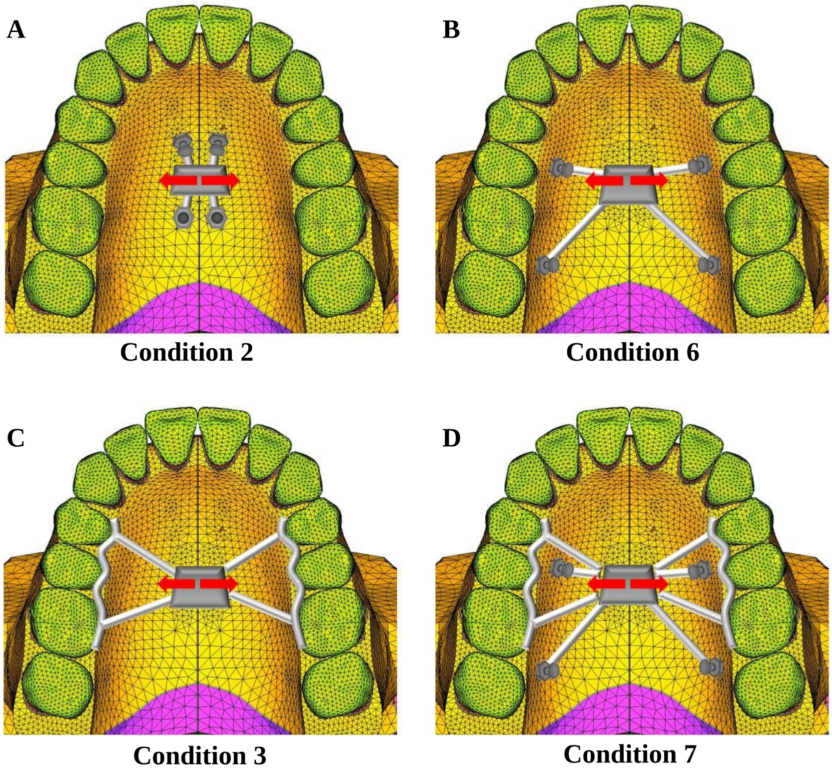


Figure 4. Appliance design and experimental conditions 6 and 7. A, Bone-borne RPE with 4 miniscrews on midpalatal area; B, bone-borne RPE with 4 miniscrews on lateral palatal slope; C, MARPE with 4 miniscrews on midpalatal area; D, MARPE with 4 miniscrews on lateral palatal slope.

3. Finite element analysis

ANSYS version 10.0 (ANSYS, Swanson Analysis System of USA, Canonsburg, PA, USA), a general program for the interpretation of finite elements, was used to analyze the force system. The components used in model construction were configured as a regular tetrahedron, with 41,480 model elements and 158,070 nodes. The base of model, the foramen magnum, was constrained in its displacement by the X, Y, and Z directions.

The conventional RPE appliance used in this study was the hyrax type. Each turn of the screw induced a 0.2-mm separation of the suture. The force ranged between 3 and 10 lbs[30,31], with multiple turns generating loads > 20 lbs. The stress and displacement produced by each appliance were analyzed with 1 turn of the screw and a maximum force of 10 lbs.

Displacements were measured on the x-, y-, and z-axes (transverse, anteroposterior, and sagittal planes, respectively). Medial, posterior, and superior directions were + value. The internal stress reaction was measured by the von Mises stresses (g/mm^2). The stress distribution is presented by color contour bands, in which different colors represent different stress levels in the deformed state.

III. Results

1. Effect of tooth- or bone- borne appliances

1) Stress distribution in the circumaxillary structures. (Fig 5, 6)

Figures 5 and 6 show the distribution of stresses produced by activation of the RPE appliance over the various sutures and bones of the craniofacial complex. The stress distribution represents the von Mises stresses, with different colors corresponding to varying amounts of stress. Positive or negative values in the stress spectrum column indicate tension or compression, respectively.

In condition 1 (tooth-borne RPE), the buccal plate of the anchor teeth and frontal process of the maxillary bone showed a high stress value (224.7 g/mm^2) that would cause side effects during nonsurgical RPE treatment. In condition 2 (bone-borne RPE), although there were few factors that could cause side effects, the stress was highly concentrated around the miniscrews (1899.9 g/mm^2) and was not transferred effectively to the basal bone or sutures. In condition 3 (combination type of conditions 1 and 2), the maximum stress value of 558.6 g/mm^2 was focused around the miniscrews. However, the stress was relatively evenly distributed among the circumaxillary structures. The stress around the anchor teeth and frontal process of the maxillary bone (186.5 g/mm^2) was reduced compared to condition 1(Table 2).

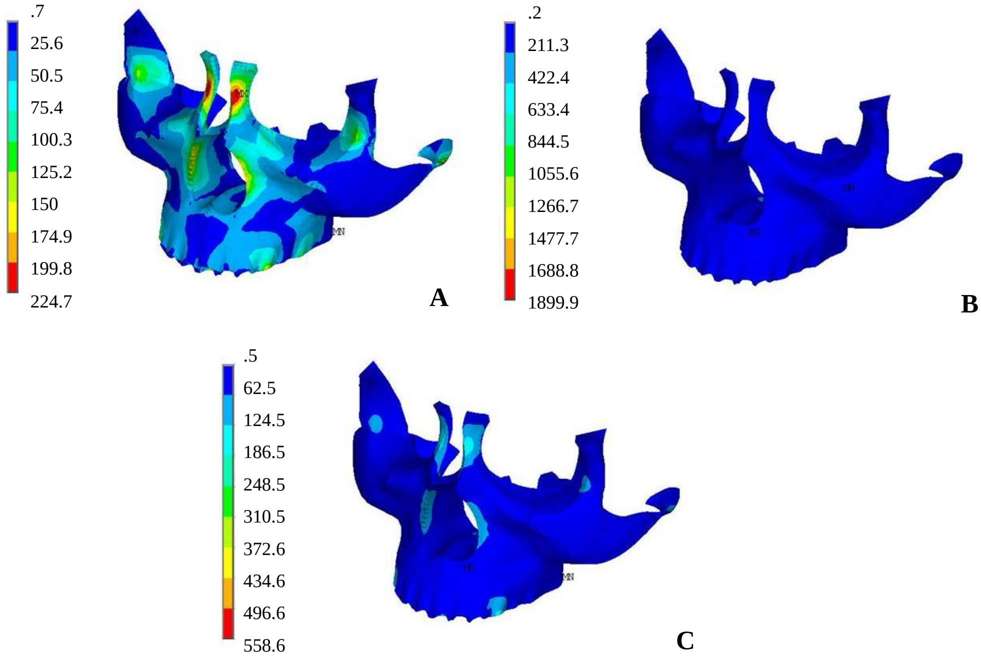


Figure 5. Frontal view for the von Mises stress distribution (g/mm^2). A, Tooth-borne RPE; B, bone-borne RPE; C, MARPE; MX, maximum stress area; MN, minimum stress area.

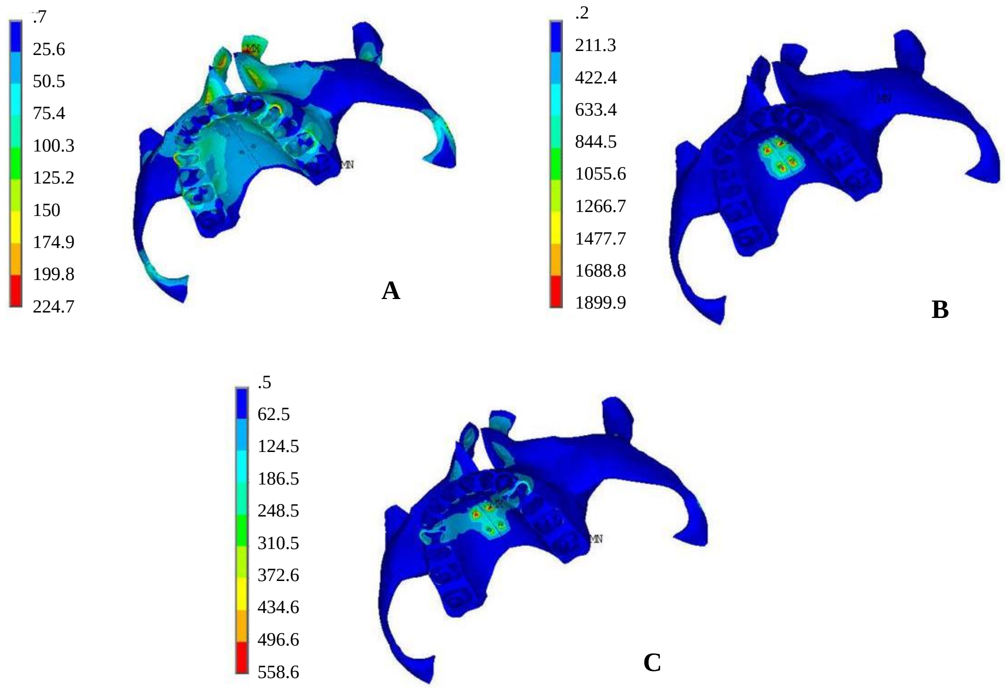


Figure 6. Horizontal view for the von Mises stress distribution (g/mm^2). A, Tooth-borne RPE; B, bone-borne RPE; C, MARPE; MX, maximum stress area; MN, minimum stress area.

2) The von Mises stress distribution on sutures.

Maximum von Mises stresses were experienced by the midpalatal, palatomaxillary, frontomaxillary, zygomaticomaxillary, and palatosphenoid sutures (Table 2). In condition 2, although the maximum stress was observed on the midpalatal and palatomaxillary sutures, the stress was locally concentrated and was not distributed through the whole suture. In conditions 1 and 3, although the maximum stress value on the midpalatal and palatomaxillary sutures was less than that in condition 2, the stress was relatively evenly distributed through the whole suture (Fig. 7).

Table 2. Comparison of von Mises stresses(g/mm^2) on various sutures and buccal plate of anchor teeth

Location	Condition 1 Tooth-borne RPE	Condition 2 Bone-borne RPE	Condition 3 MARPE
Midpalatal suture	22.0	48.2	22.5
Palatomaxillary suture	20.5	36.2	20.2
Frontomaxillary suture	58.0	8.9	38.3
Zygomaticomaxillary suture	12.9	2.0	8.5
Palatosphenoid suture	19.3	8.9	17.0
Buccal plate U4	196.2	0.3	124.5
Buccal plate U6	174.5	0.3	62.5

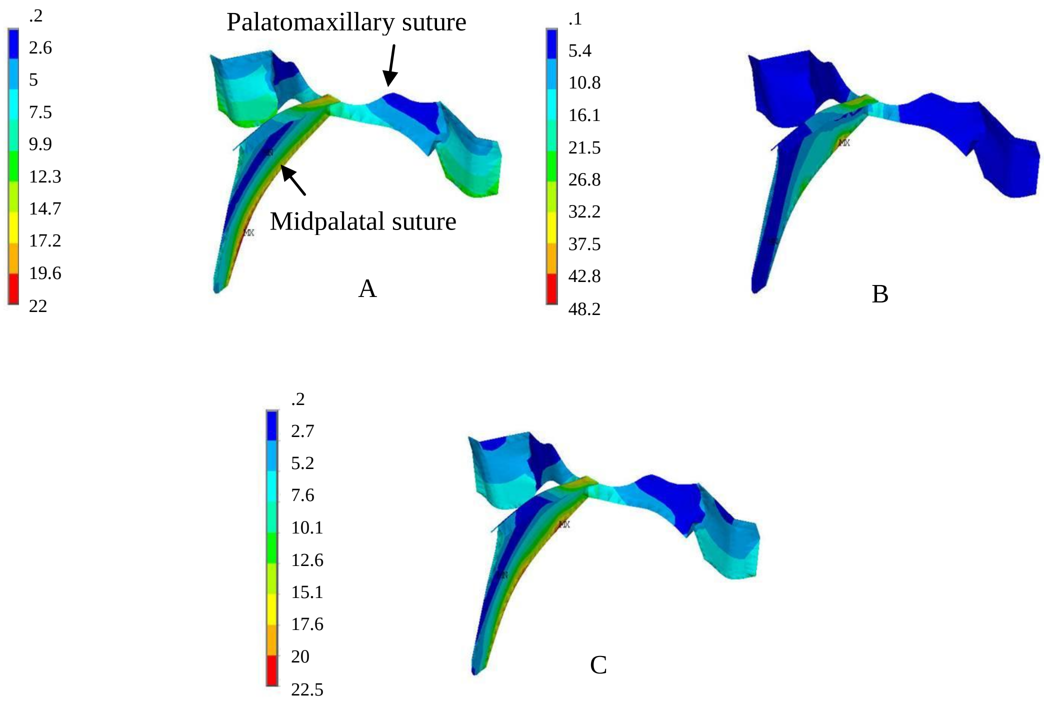


Figure 7. The von Mises stress distribution (g/mm^2) on the midpalatal suture. A, Tooth-borne RPE; B, bone-borne RPE; C, MARPE; MX, maximum stress area; MN, minimum stress area.

3) Displacement of anchor teeth

Displacements of the anchor teeth were measured along the x-, y-, and z- axes, with positive values set for the medial, posterior, and superior directions. The displacement was analyzed by determining the coordination and moving distance of the midpoint of incisal edge and root apex for the central incisor, buccal cusp tip and the buccal root apex for the first premolar, and the mesiobuccal cusp tip and mesiobuccal root apex for the first molar (Table 3).

There were only a few dentoalveolar effects seen in condition 2, because the appliance was not connected to the anchor teeth. Conditions 1 and 3 showed similar displacement patterns of the anchor teeth. Maximum displacement in the transverse plane was seen as buccal tipping of the first premolar caused by the transverse expansion force and the first molar tipped laterally as well (Fig. 8). The buccal tipping tendency of the anchor teeth and the measured displacement were decreased in MARPE (Fig. 9).

The addition of miniscrews to the conventional RPE moved the net vector of the expansion force upward and dispersed the expansion force into the miniscrews and teeth. The displacement pattern in the y- and z-axes was related to the downward and forward displacement of the maxilla due to RPE treatment.

Table 3. Amount of displacement(mm) of teeth

			Condition 1 Tooth- borne RPE	**Condition 2 Bone- borne RPE**	**Condition 3 MARPE**
X*	CI	cusp tip	-4.83E-04	4.63E-06	-3.43E-04
		apex	-2.94E-04	-8.93E-05	-2.28E-04
	PM	cusp tip	-1.05E-02	-1.18E-03	-9.69E-03
		apex	3.96E-04	-5.32E-04	2.52E-04
	M1	cusp tip	-7.40E-03	-1.55E-03	-4.34E-03
		apex	-2.20E-04	-7.78E-04	-4.80E-04
Y†	CI	cusp tip	-2.51E-02	-4.45E-03	-1.67E-02
		apex	-1.02E-02	-1.84E-03	-6.88E-03
	PM	cusp tip	-2.05E-02	-3.20E-03	-1.30E-02
		apex	-9.93E-03	-9.97E-04	-6.53E-03
	M1	cusp tip	-2.49E-02	-3.06E-03	-1.61E-02
		apex	-1.11E-02	-1.30E-03	-7.25E-03
Z‡	CI	cusp tip	-7.76E-02	-1.33E-02	-5.13E-02
		apex	-6.68E-02	-1.14E-02	-4.41E-02
	PM1	cusp tip	-6.04E-02	-1.01E-02	-3.86E-02
		apex	-6.04E-02	-9.78E-03	-3.97E-02
	M1	cusp tip	-4.86E-02	-8.00E-03	-3.20E-02
		apex	-4.88E-02	-7.98E-03	-3.21E-02

CI, central incisor; PM1, 1st premolar; M1, 1st molar. ;* Bucco-lingual: (+) lingual, (-) buccal direction; † Anterio-posterior: (+) posterior, (-) anterior direction; ‡ Superio-inferior: (+) superior, (-) inferior direction.

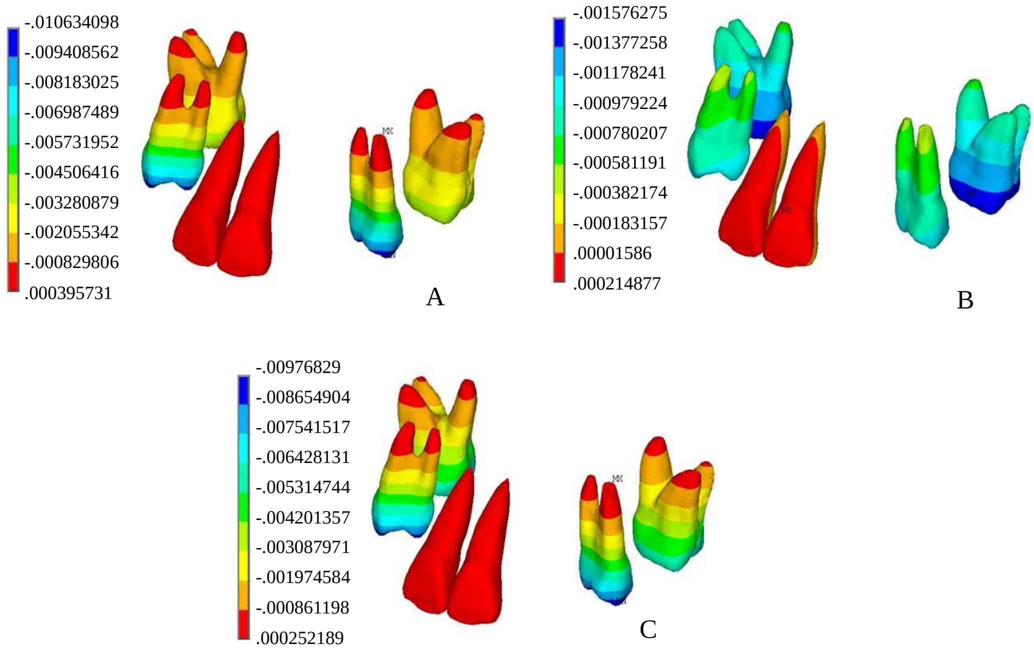


Figure 8. Displacement of teeth (mm) on the x-axis, transverse plane. A, Tooth-borne RPE; B, bone-borne RPE; C, MARPE; MX, maximum stress area; MN, minimum stress area.

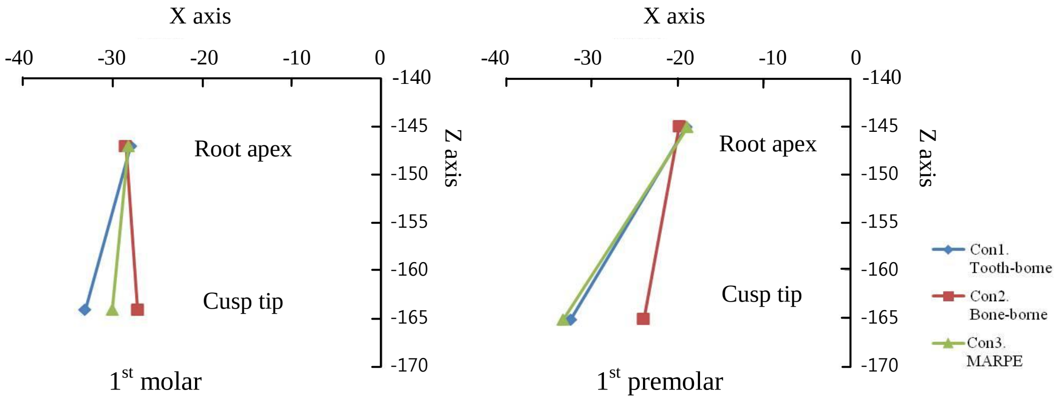


Figure 9. Changes of axes of anchor teeth in X-Z plane. Axes of anchor teeth are represented by magnifying the amount of displacement 500 times.

4) Comparison of the stress distribution of each device

To evaluate the effect of each device, the stress distribution pattern and maximum von Mises stresses on specific areas were compared (Table 4). Bone-borne RPE was expected to be the ideal device for nonsurgical RPE treatment in adults, without side effects. However, the expansion force generated by the screw was concentrated on a small area around the miniscrews and was not transferred to the basal bone. The maximum stress value was extremely high and was localized on the middle area of the midpalatal suture. With the MARPE, although the maximum stress was observed around the miniscrews, the value was much smaller than that with the bone- borne RPE. Moreover, the von Mises stress was evenly distributed through the midpalatal suture. Stresses on the buccal plates of the first premolar and first molar were reduced by one-third compared to those with the tooth-borne RPE.

Table 4. Comparison of stresses (g/mm^2) and distribution patterns

Location	Condition 1 Tooth-borne RPE	Condition 2 Bone-borne RPE	Condition 3 MARPE
Buccal plate of anchor teeth	High	Low	Middle
Miniscrew	N/A	1899.9	558.6
Distribution pattern (midpalatal suture)	Overall area	Middle	Overall area
Maximum stress value (circumaxillary structure)	224.7	1899.9	558.6
Maximum stress location (circumaxillary structure)	Around anchor teeth and frontal process of maxillary bone	Around miniscrew	Around miniscrew; Even distribution on basal bone

2. Effect of the number of miniscrews

Figure 10 shows the effect of the number of miniscrews on the stress distribution. The stress was extremely concentrated around the miniscrews, and the expansion force was not transferred to the basal bone in any condition. When 2 or 4 miniscrews were added to the bone-borne RPE, the stress was focused on the miniscrews in front of the palatal expander, rather than spread among all of the miniscrews and the basal bone (Table 5).

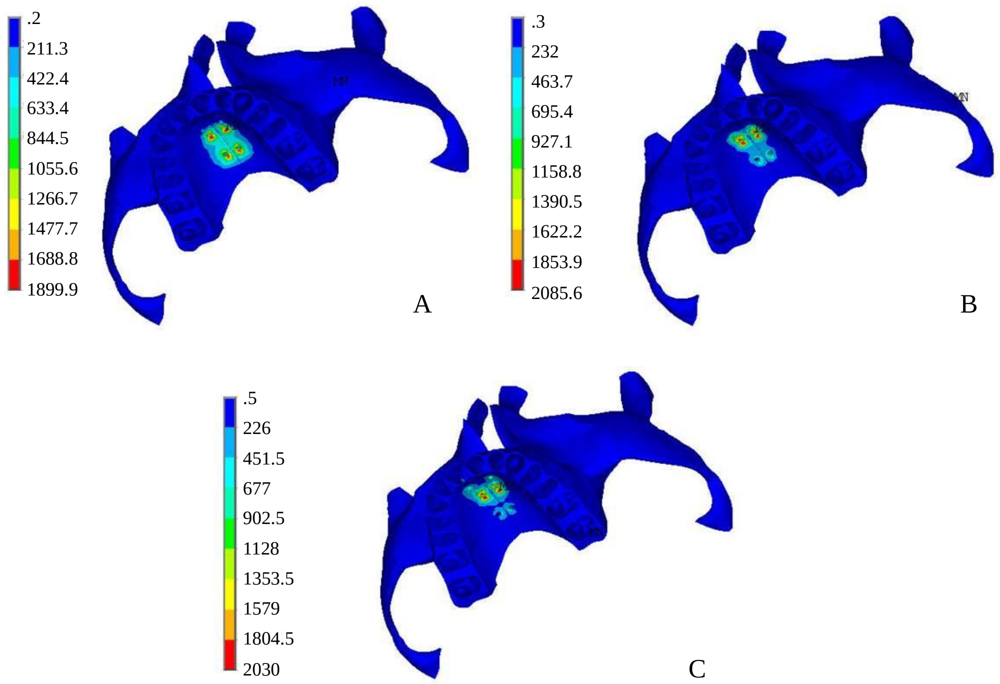


Figure 10. von Mises stress distribution (g/mm^2) according to the number of miniscrews. A, Condition 2 (Bone-borne RPE with 4 miniscrews); B, condition 4 (bone-borne RPE with 6 miniscrews); C, condition 5 (bone-borne RPE with 8 miniscrews); MX, maximum stress area; MN, minimum stress area.

Table 5. Stress (g/mm^2) distribution patterns on various circumaxillary structures according to the number of miniscrews

Location	Condition 2 4 miniscrews	Condition 4 6 miniscrews	Condition 5 8 miniscrews
Buccal plate of anchor teeth	0.3	0.4	0.5
Miniscrew	1899.9	2085	2030
Distribution pattern and maximum stress value (midpalatal suture)	Middle 48.2	Middle 31.3	Middle 29.2
Maximum stress value and location (circumaxillary structure)	1899.9 Around miniscrew	2085 Around miniscrew	2030 Around miniscrew

3. Effect of miniscrew position

For bone-borne RPE and MARPE, the stress was evenly distributed and the maximum stress value was decreased in conditions 6 and 7 when 4 miniscrews were used on the lateral palatal slope. The maximum stress was located around the miniscrews in all conditions. In bone-borne RPE, the maximum stress values were 1899.9 and 586.1 g/mm^2 with midpalatal and lateral miniscrews, respectively. In MARPE, these values were 558.6 and 310.1g/mm^2, respectively (Table 6). The expansion force was transferred to the maxillary basal bone and circumaxillary sutures more evenly and widely when the miniscrews were placed on the lateral palatal slope (Figs. 11–13).

There were only a few dentoalveolar effects seen in condition 2, but the amount of displacement of anchor teeth was increased in condition 6, bone-borne RPE with lateral miniscrews. In addition to increased displacement in transverse plane, buccal tipping tendency of anchor teeth was also intensified in condition 6, because maxillary bone is expanded pyramidal shape by RPE treatment[18] (Table 7). However, in condition 7, MARPE with lateral miniscrews showed different displacement pattern. Buccal tipping tendency of anchor teeth, especially 1^{st} premolar, was decreased and the amount of expansive displacement was increased compared to condition 3, MARPE with midpalatal miniscrews. The stress around anchor teeth was reduced by using miniscrews on lateral palatal slope, so it may cause decrease of buccal tipping tendency even though transverse displacement of anchor teeth was increased. The amount of displacement in condition 7 was approximately intermediate value of bone-borne RPE with lateral miniscrews and conventional RPE.

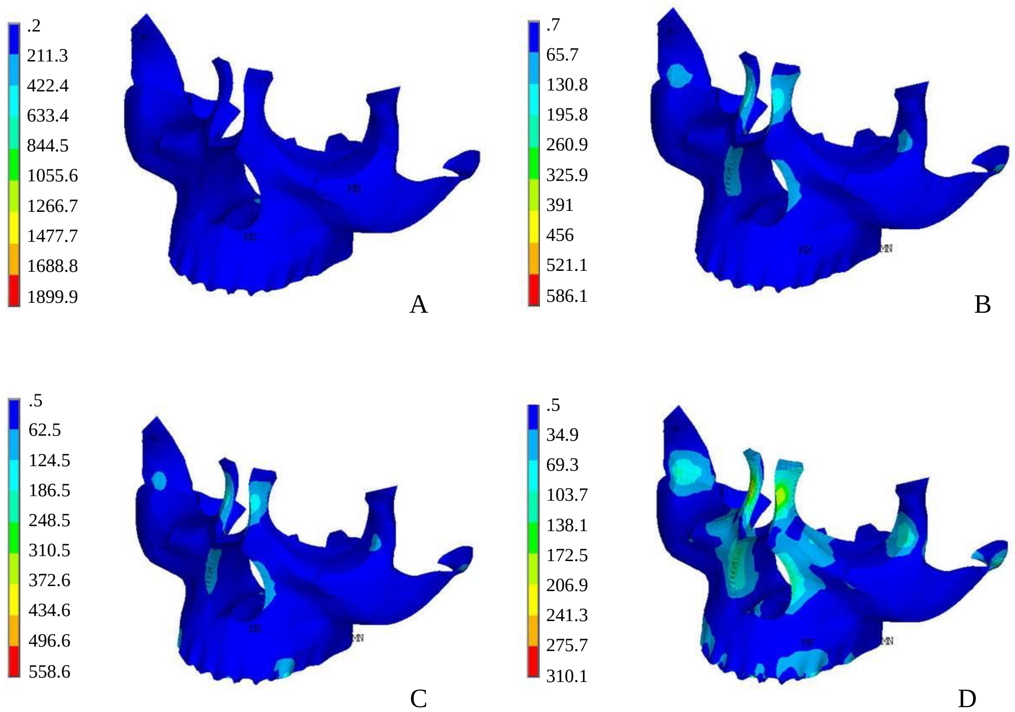


Figure 11. Frontal view of the von Mises stress distribution (g/mm^2) according to the position of miniscrews. A, Condition 2 (Bone-borne RPE with midpalatal miniscrews); B, condition 6 (bone-borne RPE with lateral miniscrews); C, condition 3 (MARPE with midpalatal miniscrews); D, condition 7 (MARPE with lateral miniscrews); MX, maximum stress area; MN, minimum stress area.

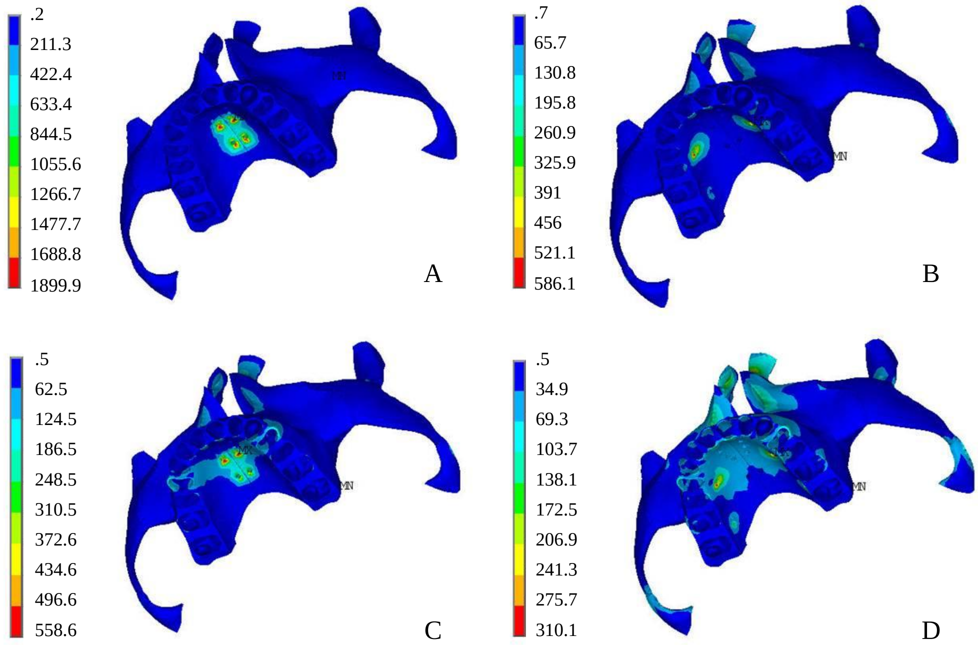


Figure 12. Horizontal view of the von Mises stress distribution (g/mm^2) according to the position of miniscrews. A, Condition 2 (Bone-borne RPE with midpalatal miniscrews); B, condition 6 (bone-borne RPE with lateral miniscrews); C, condition 3 (MARPE with midpalatal miniscrews); D, condition 7 (MARPE with lateral miniscrews); MX, maximum stress area; MN, minimum stress area.

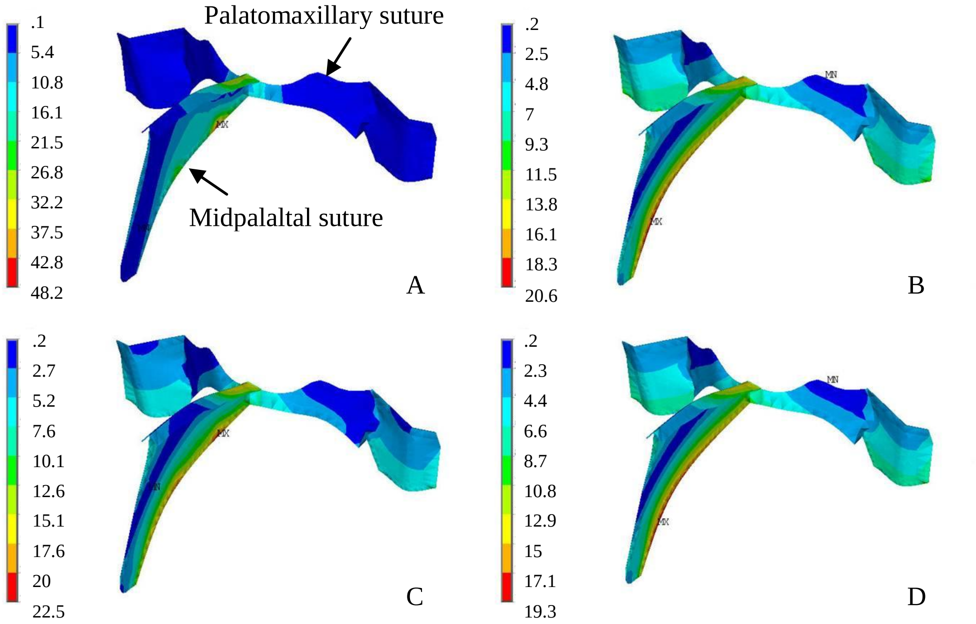


Figure 13. The von Mises stress distribution (g/mm^2) on the midpalatal and palatomaxillary sutures. A, Condition 2 (Bone-borne RPE with midpalatal miniscrews); B, condition 6 (bone-borne RPE with lateral miniscrews); C, condition 3 (MARPE with midpalatal miniscrews); D, condition 7 (MARPE with lateral miniscrews); MX, maximum stress area; MN, minimum stress area.

Table 6. Stress (g/mm^2) distribution patterns on various circumaxillary structures according to the miniscrew position

	Bone-borne RPE		**MARPE**	
Location	Condition 2 Midpalatal	Condition 6 Palatal slope	Condition 3 Midpalatal	Condition 7 Palatal slope
Buccal plate U4	0.3	0.7	124.5	103.7
Buccal plate U6	0.3	0.7	62.5	34.9
Miniscrew	1899.9	586.1	558.6	310.1
Midpalatal surture	48.2	19.3	22.5	20.6
Palatomaxillary suture	36.2	17.4	20.2	18.6
Maximum stress value	1899.9	586.1	558.6	310.1
Distribution pattern	Around miniscrew	Even distibution on basal bone	Even distribution on basal bone	Most even distribution

Table 7. Amount of displacement(mm) of teeth according to the miniscrew position

			Bone-borne RPE		MARPE	
			Condition 2 Midpalatal	**Condition 6 Palatal slope**	**Condition 3 Midpalatal**	**Condition 7 Palatal slope**
X*	CI	cusp tip	4.63E-06	-3.93E-04	-3.43E-04	-4.40E-04
		apex	-8.93E-05	-2.67E-04	-2.28E-04	-2.81E-04
	PM	cusp tip	-1.18E-03	-2.20E-03	-9.69E-03	-7.04E-03
		apex	-5.32E-04	-5.52E-04	2.52E-04	-4.31E-05
	M1	cusp tip	-1.55E-03	-2.17E-03	-4.34E-03	-4.09E-03
		apex	-7.78E-04	-8.45E-04	-4.80E-04	-6.37E-04
Y†	CI	cusp tip	-4.45E-03	-1.89E-02	-1.67E-02	-2.17E-02
		apex	-1.84E-03	-7.80E-03	-6.88E-03	-8.89E-03
	PM	cusp tip	-3.20E-03	-1.79E-02	-1.30E-02	-2.01E-02
		apex	-9.97E-04	-7.22E-03	-6.53E-03	-8.43E-03
	M1	cusp tip	-3.06E-03	-1.80E-02	-1.61E-02	-2.13E-02
		apex	-1.30E-03	-8.53E-03	-7.25E-03	-9.70E-03
Z‡	CI	cusp tip	-1.33E-02	-5.84E-02	-5.13E-02	-6.70E-02
		apex	-1.14E-02	-5.03E-02	-4.41E-02	-5.77E-02
	PM1	cusp tip	-1.01E-02	-4.70E-02	-3.86E-02	-5.28E-02
		apex	-9.78E-03	-4.52E-02	-3.97E-02	-5.20E-02
	M1	cusp tip	-8.00E-03	-3.68E-02	-3.20E-02	-4.22E-02
		apex	-7.98E-03	-3.71E-02	-3.21E-02	-4.24E-02

CI, central incisor; PM1, 1st premolar; M1, 1st molar. * Bucco-lingual (+) lingual, (-) buccal direction; † Anterio-posterior (+) posterior, (-) anterior direction; ‡ Superio-inferior (+) superior, (-) inferior direction.

IV. Discussion

In this study, analysis with FEA showed that the conventional RPE induced the highest stress on the frontal process of the maxilla and anchor teeth, but not on the suture area. Thus, the RPE produced an expansion force at the intermaxillary suture as well as high forces on various structures in the craniofacial complex. With MARPE, the stress was distributed relatively evenly, and the stress value was reduced on the buccal plate of the anchor teeth. The addition of miniscrews moved the net vector of the expansion force closer to the center of resistance of the basal bone. As a result, the buccal tipping tendency of the anchor teeth and the total displacement were decreased compared with the tooth-borne RPE. Bone-borne RPE was expected to be most effective as an alternative to SARPE. However, use of this appliance highly concentrated the stress around the miniscrews, which could lead to miniscrew failure. Additionally, an extremely high level of force could be required to separate the sutures, because the point of force application was very close to the center of resistance of the maxilla.

In a current study about the effects of miniscrews orientation on the stability and resistance to failure[32], the maximum force at failure was 87±27.2N - 342±80.9N($P<0.001$) in the human mandible. The vector of shear force and the long axis of miniscrews affect to the values. The physiologic threshold[33,34] of bone strain for the maxilla has not been determined yet, but strain is related to the stress and the area force applied. If accumulated strain caused from multiple jack screw turning is exceeded the physiologic strain limits, loss of marginal bone would be the result of mechanical stress[35] and it leads to failure of miniscrews.

Although the stress concentration pattern was unchanged when the number of miniscrews was increased, the stress distribution pattern significantly differed depending on the miniscrew position. For the bone-borne RPE and MARPE, the stress was more evenly distributed and the maximum stress value was decreased when the 4 miniscrews were placed on the lateral palatal slope rather than on the midpalatal area. The direction of the expansion force generated from the expander is similar to the miniscrew axis; thus, the force does not act as a lateral tipping force to the miniscrews, but minimizes the stress around them. The efficiency of the expansion force may be improved, because the distance between the center of resistance of the basal bone and the force application point was farther than when midpalatal miniscrews were used.

However, it is needed to consider how to connect miniscrews to the device for clinical application. In this finite element model, miniscrews were connected to the RPE using 0.8mm ss wire and it was assumed to act as 1-unit device without loss of expansion force on conjunction area. The efficiency of expansion force delivered to the miniscrews would be decreased according to the miniscrew position, the length of connecting wire and the solidity of conjunction between wire and miniscrews. Considering the axis of miniscrews and the direction of connecting wire movement as the RPE expanded is needed to determine the appliance design as well.

The MARPE represents a simple modification of the conventional RPE appliance. The main difference is the incorporation of several miniscrews to ensure expansion of the underlying basal bone and to maintain bone separation during the consolidation period. Miniscrew placement is a simple procedure that does not require osteotomy. When selecting the number and location of miniscrews, one must consider whether the connected miniscrews can withstand the expansion force. The appropriately designed appliance would be helpful to reduce side effects of conventional RPE treatment in adults and it would also maintain the efficiency of expansion force at the same time. The results of this and previous studies[5,6] suggest that MARPE may serve as an effective treatment modality for young adults with transverse deficiency from late teens to the mid-twenties.

The FEA method permits the simulation of clinical orthodontic systems to study biomechanical variables induced by various external forces in 3D space. The accuracy of the results depends on the accuracies of the modeling procedure, element density, and material properties. In this study, skull modeling was performed by using data from individualized CT images, which were taken at 2-mm intervals for good continuity and accuracy. The maxillary dentoalveolar arch, orthodontic miniscrews, and RPE appliance were added artificially into the whole skull model with the appropriate proportional relationship.

Because of the complexity of bone structures and the extensive network of sutures, the exact mechanical properties of sutures at each stage of human development are not well defined. Recent reports of the nanomechanical properties of rat cranial sutures obtained with atomic force microscopy (AFM) indicate that the elastic moduli of such sutures vary from 0.64 to 1371 MPa[36]. Using nanoindentation by AFM, Radhakrishnan et al.[37] demonstrated that the average elastic moduli of the zygomaticotemporal, nasofrontal, and pre-maxillomaxillary sutures in rabbits were 1.20, 1.16, and 1.46 MPa, respectively.

The degree of ossification of the circumaxillary sutures can affect the material properties. Several studies have examined the mechanical properties of unossified[38], completely ossified[23], and partially ossified sutures. Provatidis et al.[21] suggested an elasticity modulus of 500 MPa for partially ossified sutures. The material properties of craniofacial sutures also vary according to the region of ossification. Assigning appropriate values to the material properties for each condition is technically difficult, and slight variations in these values may not significantly affect the overall displacement and stress distribution patterns. Therefore, in this study, the craniofacial sutures were assumed to be isotropic, homogeneous, and linearly elastic, and the elastic modulus was determined on the basis of a previous study[21] using a similar skull model.

Research on the physical properties of living structures is not yet sufficient. Errors from deformations of the bone and appliances and the effects of soft tissue were not considered. Future studies will aim to model the suture as a viscoelastic material with hardening properties and under growing conditions. Nevertheless, when supplemented with clinical, cytological, and biochemical research, the results from this study may be effectively applied in the clinical field.

These results provide additional explanations about the mechanical reactions of the bony tissue, which are the first step in the complex process of tissue response to expansion force. The findings could help to elucidate the therapeutic effects of and mechanisms by which appliances act on the basal bones and sutures of the craniofacial complex.

V. Conclusions

This study evaluated the stress distribution and displacement of various craniofacial structures after nonsurgical RPE in young adults according to appliance design using 3D FEA.

1. Conventional RPE induced the highest stress, although the maximum stress was on the frontal process of the maxilla and around the anchor teeth and not on the suture area. As the combination type of bone- and tooth-borne RPE, MARPE showed a relatively even stress distribution and reduced stress on the buccal plate of the anchor teeth. Bone-borne RPE was expected to be the most effective as an alternative of SARPE. However, the stress was highly concentrated around the miniscrews, rather than being transferred to the basal bone and the whole midpalatal suture.

2. Even when 2 or 4 miniscrews were added to the bone-bone RPE, the stress remained extremely concentrated around the miniscrews, and the expansion force was not transferred to the basal bone under any condition.

3. With both the bone-borne RPE and MARPE with 4 miniscrews, the stress was more evenly distributed and the maximum stress value was decreased when the miniscrews were located on the lateral palatal slope compared to when they were located in the midpalatal area.

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국문요약

미니스크류 보강형 구개확장장치의 효과에 대한 유한 요소 분석

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성 의 향

사춘기 이후 성인에서의 악정형적 상악골 확장은 연령 증가에 따른 봉합의 조직학적 구조 변화와, 상악골을 둘러싼 구조물들의 저항으로 인해, 성공 가능성이 낮다고 알려져 있어 수술적 방법을 동반한 SARPE가 보편적으로 이용되어 왔다. 그러나 경제적, 심리적 부담과 외과적 술식상의 위험 및 상악의 반복적인 수술로 인한 치료의 복잡성 증가로 인해, 최근 횡적 부조화를 가진 성인 환자에서 surgical risk 를 줄이려는 노력이 계속되고 있다. 그러나 아직 상악골 확장에 이용되는 장치들, conventional RPE, bone-borne RPE 그리고 이들의 조합형인 MARPE에 따른 응력 분산 효과 및 변위양상에 대하여는 잘 알려져 있지 않기 때문에 본 연구에서는 유한요소 분석법을 이용하여 상악골 확장치료 시 다양한 장치디자인, 미니스크류의

개수, 미니스크류의 위치에 따른 상악골 주위 구조물의 응력분포 및 고정원 치아의 변위양상을 평가해 보고자 하였다. 20 세 성인 남성 skull model 을 참고로 3D 유한요소분석 모델을 제작하고 다양한 장치를 고안하여 확장력을 부여한 결과 다음과 같은 결과를 얻었다.

1. Tooth borne RPE 의 경우에서 전반적인 기저골에서의 응력분포가 보이나 상악골의 frontal process와 고정원 치아의 협측 피질골에 응력이 집중되어 나타났으며, bone borne RPE 에서는 기저골 레벨에서의 응력분포는 거의 보이지 않고 미니스크류 주위에 모든 응력이 집중되었다. 조합형인 MARPE 에서는 비교적 고른 응력분포를 보임과 동시에 고정원 치아의 협측 피질골에 집중되던 응력이 절반 정도로 감소하였다.

2. Bone-bonrne RPE 에 총 4 개, 6 개, 8 개의 미니스크류를 이용하여 비교한 결과 미니스크류의 개수를 추가하는 것은 응력 분포 양상에 변화를 가져오지 못하였고 모두 미니스크류 주변에 응력이 집중되었다.

3. Bone-borne RPE 와 MARPE 에서 4 개의 미니스크류를 구개 정중부와 Lateral palatal slope 부위에 적용한 결과 두 가지 장치 모두 Lateral palatal slope 에 미니스크류를 적용하였을 때 더욱 효과적으로 응력이 기저골 전체에 고르게 분포하였다.

핵심 단어: 유한 요소 분석, 구개확장장치, 미니스크류, 응력분포